4DVAR for Global Atmospheric Numerical Weather Prediction

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LONG-TERM GOALS

The long-term goal of this RTP project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the global atmospheric state. This situational awareness is a key aspect of information superiority in the DoD's strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing NOGAPS[1] with the best possible set of initial conditions through the use of a next generation global atmospheric 4D variational (4DVAR) data assimilation system, NAVDAS-AR[2].

OBJECTIVES

The objective of this project is to construct and transition a 4DVAR global atmospheric data assimilation system for NOGAPS to the Fleet Numerical Meteorology and Oceanography Center (FNMOC). This system, NAVDAS-AR, represents the first operational, weak constraint, 4DVAR atmospheric data assimilation system in the world. In this context, "weak constraint" means that the atmospheric forecast model is not considered a "perfect" model, but rather is assumed to have errors. This enables the most optimal solution. NAVDAS-AR will provide high fidelity, dynamically consistent analyses for NWP model initialization and for warfighter support, and will be capable of efficiently handling large numbers of observations that may be irregularly distributed in space and time, and/or indirectly related to the model state variables (e.g., satellite radiances or wind vectors).

APPROACH

Our approach is to build on the prototype of NAVDAS-AR (Xu et al 2005, and Rosmond and Xu 2006) that has been developed and successfully applied to the global 4DVAR data assimilation application using the NOGAPS prediction model as a dynamic constraint. This project, which is a follow-up to a NRL ongoing in-house 6.2 data assimilation project, will expand this prototype to a next-generation operational global atmospheric data assimilation system. We will leverage the existing NAVDAS and NOGAPS infrastructures to provide the pre- and post- analysis processes. The system will be thoroughly tested using scientific studies, and comprehensive data assimilation and forecast experiments. Although the goals are ambitious, they are realistic because the theoretical basis for the project is already in place owing to great progress made in our 6.1 and 6.2 in-house data assimilation projects on variational data assimilation.

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[1] NOGAPS: Navy Operational Global Atmospheric Prediction System
[2] NAVDAS-AR: NRL Atmospheric Variational Data Assimilation System – Accelerated Representer

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WORK COMPLETED

The following is a list of work completed related to this project during FY06.

1. Developed and tested a new efficient computational algorithm for initial error covariance convolution.
2. Increased the scalability of NAVDAS-AR to O(100) processors in distributed computer architectures.
3. Developed and tested a new stopping algorithm that requires fewer iterations to achieve the same accuracy.
4. Completed a generalized framework of observation operators for NAVDAS-AR and started to assimilate AMSU-A radiances.
5. Ported the system to the NRL Linux cluster and HPC computers to facilitate subsequent extensive data assimilation testing.

These FY06 accomplishments are critical for conducting subsequent comprehensive data assimilation tests planned for FY07.

RESULTS

The following results represent some highlights of the several significant accomplishments of this project during FY06.

A new stopping algorithm for NAVDAS-AR

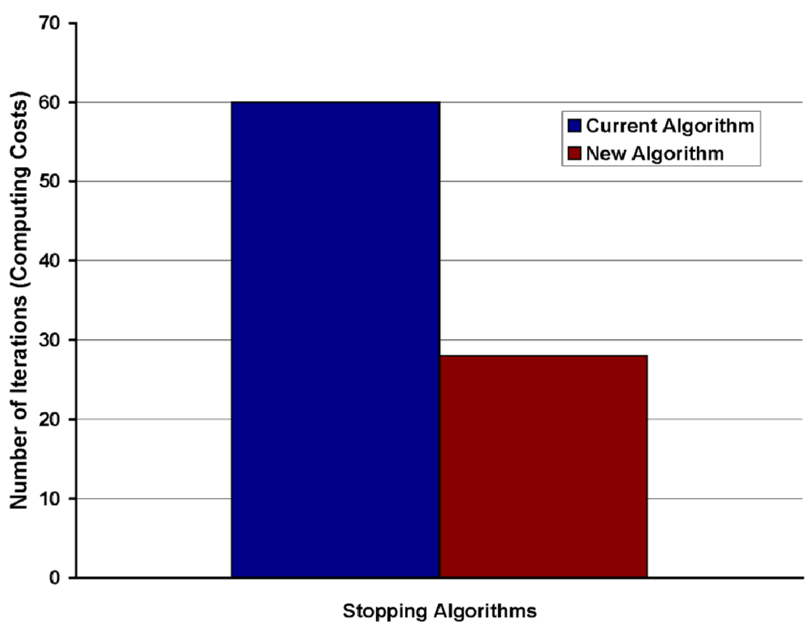

Figure 1: Total number of iterations required for new and current stopping algorithms in NAVDAS-AR [Graphic shows the new stopping algorithm requires only half of the computation (number of total iterations) to achieve the same accuracy]

An outer-inner loop strategy is used in NAVDAS-AR. While the outer loop deals with the nonlinearities that commonly exist in global atmospheric processes, the inner loop deals strictly with the linearized process related to the minimization along a previous basic state. An iterative conjugate gradient solver is used in the inner loop to minimize a four dimensional cost function that represents the misfit between the initial condition, the model, the observations and truth, respectively. The total computational cost of NAVDAS-AR approximately equals the total number of inner loop iterations required from all the outer loops. Typically, we should get the 4DVAR solution as accurate as possible in the first outer loop, such that we are able to capture the majority of the useful information in the first outer loop. The original version of NAVDAS-AR reflects this practice. However, we recently found that it is much more computationally efficient to relax the stopping criteria throughout the whole data assimilation process (including the first outer loop) to achieve the same analysis accuracy. The advantage of the new stopping algorithm is clearly demonstrated in Figure 1.

Recent improvements to NAVDAS-AR

Recent improvements to NAVDAS-AR have been very dramatic. The most computationally expensive part of the original NAVDAS-AR is the convolution of the initial background error covariance with the initial state vector. There were two main issues associated with cost in the original version, namely the MPI scalability and the background error covariance calculations, where matrix operations dominate. We have made significant gains (particularly on the IBM architecture computers), not only in the NAVDAS-AR itself, but also the NOGAPS forecast model. The following are comparisons of typical speedups for NAVDAS-AR (the "sweep" algorithm) and the NOGAPS forecast model.

Table 1: Computational requirement in seconds for original and new NAVDAS-AR and NOGAPS, respectively [Table shows that the new AR and NOGAPS require less than 60% and about 70% of the computation required by the original AR and NOGAPS, respectively.]

	NAVDAS-AR (50 iterations)	NOGAPS (120 hr forecast)
Original	1620 secs	4540 secs
New	940 secs	3244 secs

In both cases the most dramatic speed decreases come from consistent use of math libraries that are optimized for the platform we are running on, while maintaining code portability between different platforms).

In NAVDAS-AR, it is also necessary to switch between lat-lon 'space' and AR volume (prism) 'space' in the background covariance convolution. In the past, this was been done in a variety of ways: the late Dr. Roger Daley used a 'master-slave' MPI algorithm lifted directly from NAVDAS[3]; we switched this to collective MPI calls to exploit the static grid of the AR covariance calculations. Both of these approaches scale very poorly, but Dr. Tom Rosmond recently developed a point-to-point MPI algorithm that scale well. The cost of the lat-lon to AR volume transfers are much less than the AR volume to lat-lon transfers. Fortunately, our new method applies to the latter, so the benefits are great. On 40 processors the new method is typically 5 times faster than the old (100 secs vs. 500 secs), so

[3] NAVDAS: NRL Atmospheric Variational Data Assimilation System

about 50% of the total AR speedup is due to this change, the other 50% from the switch to the platform specific libraries.
In summary, these changes will have a dramatic impact on our throughput for AR experiments. A full AR update cycle on the FNMOC IBM, including background forecast, QC, AR solution, SLP analysis, post-processing, graphics, and statistics, takes about 30 minutes. The operational NAVDAS, which is run on the FNMOC SGI machines, also takes around 30 minutes. The recent performance enhancements make employing higher inner loop resolution more feasible, which is desirable, as this may be necessary for special cases, such as the assimilation of data associated with tropical cyclones.

NOGAPS 500 MB anomaly correlation using NAVADS-AR

From a theoretical point of view, NAVDAS-AR is superior to NAVDAS, in part because NOGAPS is used as a dynamical constraint and observations are assimilated at the correct observation time. It is equally important that we implement the "AR" algorithm properly, such that the theoretical superiority translates into the real gains in operational forecasts. In the past several months, we were able to directly assimilate satellite radiances, such as AMSU-A into NAVDAS-AR. Consequently, we are now able to conduct comparisons of NOGAPS forecast skill between NAVDAS-AR and NAVDAS update cycles. An important benchmark test of the skill of the data assimilation system is to compare NOGAPS 500 MB height anomaly correlations associated with the two systems.

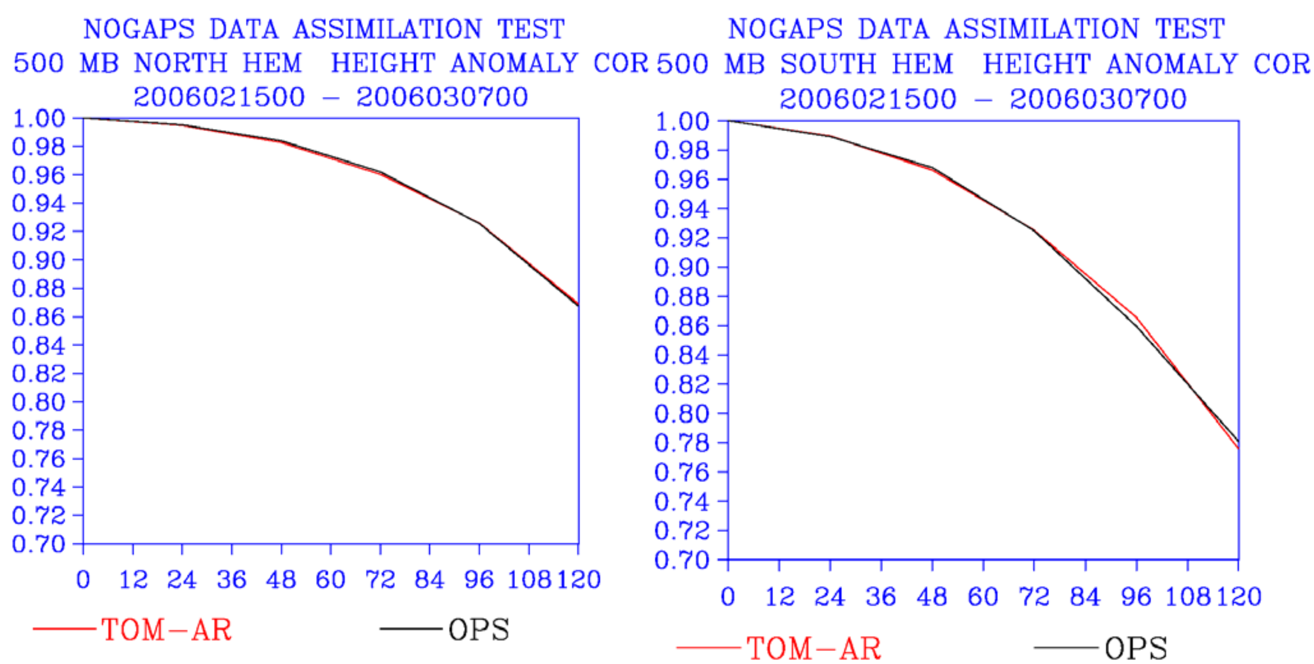

Figure 2: 500 MB forecast height anomaly correlations out to 5 days (120 hrs) for the a) Northern Hemisphere, and b) Southern Hemisphere. The solid red line is for NOGAPS forecasts initialized NAVDAS-AR analyses, while the solid black line is for NOGAPS forecasts initialized with NAVDAS analyses.

Figure 2 shows the statistic of NOGAPS 500 MB Northern and Southern Hemisphere height anomaly correlations, respectively, for up to 120 hr global forecasts. The solid red lines represent the results using NAVDAS-AR, while the solid black lines represent the results using NAVDAS. The statistics were accumulated during a three-week time period between 00Z 15 Feb 2006 and 00Z 07 March 2006. The operational run (using NAVDAS) has more data, but an optimized, operational system, NAVDAS-AR would benefit from more observations, but suffers from lack of optimization, and a known bias issue. As indicated in Figure 2, the red and black lines virtually overlap each other. Despite these discrepancies in the data used in each of the runs, the results suggest that the NAVDAS-AR forecast skill, after the first year of the RTP effort, is essentially equivalent to the operational NAVDAS. These results are very encouraging, as the observation selection and quality control have not yet been optimized for NAVDAS-AR, and the system has not been fine-tuned. Also, NAVDAS-AR will be a perfect candidate to handle the huge volume of current and future observations, such as Atmospheric infrared Sounder (AIRS), that we are planning to assimilate in the future.

IMPACT/APPLICATIONS

The current operational data assimilation system at FNMOC, NAVDAS, is based on a three-dimensional variational (3DVAR) algorithm and is cast in observation space. The 3DVAR algorithm is widely used in intermittent cycling data assimilation for the analysis of global and synoptic scales around the world. It can handle relatively slowly evolving flows and observation platforms that sample heterogeneously in space, but assumes that the observations are taken at the analysis time. However, highly intermittent flows that are not governed by simple balance relationships, and observation systems that sample irregularly in time, or with high temporal frequency, are not well accommodated within an intermittent 3DVAR framework but can be accommodated by a 4D data assimilation system. Furthermore, an intermittent 3DVAR algorithm produces a "snapshot" of the atmosphere at the center of the typical 6-hour observation time window, automatically making the resulting atmospheric analysis at least 3 hours old.

With NAVDAS-AR, a continuous picture of the atmosphere over the observation time window is produced, providing an atmospheric analysis at the end of the time window that is current rather than 3 hours old. Although NAVDAS has been quite successful, a 4D data assimilation system is a necessity to significantly improve not only the accuracy of the common operational picture required by the warfighter but also the timeliness of providing this more accurate picture to the warfighter. The advanced 4DVAR data assimilation algorithm, NAVDAS-AR, will provide the basis for this system. Only through 4DVAR algorithms can we truly exploit many of the observations from current and future observing systems. This is especially important for remotely sensed observations that are nonlinearly and indirectly related to the model state variables (e.g., satellite radiances and GPS radio occultation measurements). In addition, the computational efficiency of NAVDAS-AR with respect to the number of observations makes it more efficient than the NAVDAS 3DVAR system in handling the monumental increase in the volume of satellite data expected over the next decade.

TRANSITIONS

Improved algorithms for NAVDAS-AR have been transitioned to the 6.4 component of this project, and will ultimately be transitioned to FNMOC as the Navy's next generation operational global atmospheric data assimilation system.

RELATED PROJECTS

Some of the technologies developed for this project will be used immediately to improve the current operational data assimilation system and the observational impact in other NRL projects. NAVDAS-AR has been recognized as a viable framework for various data assimilation applications, and this is now being started in an NRL ocean data assimilation system project.

PUBLICATIONS

Rosmond, T. and L. Xu, 2006: Development of NAVDAS-AR: Non-linear formulation and outer loop tests. *Tellus*, **58A**, 45-58.

Xu, L., T. Rosmond, and R. Daley, 2005: Development of NAVDAS-AR: Formulation and initial tests of the linear problem. *Tellus*, **57A,** 546-559.

PRESENTATIONS

Rosmond, T., L. Xu, N. Baker, B. Campbell, C. Blankenship, J. Goerss, B. Ruston, and P. Pauley, 2006: Direct radiance assimilation with NAVDAS-AR. The Seventh International Workshop on Adjoint Applications in Dynamic Meteorology, Obergurgl, Austria, 8-13 October 2006.

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